Honeywell

Advanced Microturbine Systems

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Silicon Nitride Materials Development at Honeywell

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Honeywell Engines, Systems & Services

2003 Distributed Energy Peer Review

December 2-4, 2003

Washington, DC

Agenda

- Introduction
- Production Readiness Campaign
  - Program History
  - Milestone #1 Review
  - Upcoming Milestones
  - ASN Development
- Summary & Conclusions

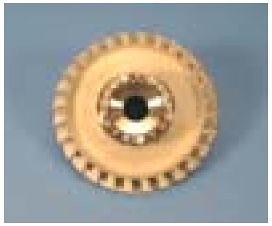
Core Team Members

- Honeywell Engines, Systems & Services
  - Dr. Bjoern Schenk, Strategic Technology, Phoenix
  - Dr. Michael Meiser, Ceramic Components, Torrance
  - Dr. Jim Wimmer, Ceramic Components, Torrance
  - JJ Nick, Ceramic Components, Torrance
  - Dr. Chien-Wei Li, Advanced Materials R&D, Morristown
  - Dr. Jim Stevenson, Advanced Materials R&D, Morristown
  - Jim Guiheen, Advanced Materials R&D, Morristown
- Fraunhofer Institute for Ceramic Technologies and Sintered Materials (IKTS), Dresden, Germany
  - Dr. Hagen Klemm, Silicon Nitride Materials Development
- H.C. Starck Ceramics, Selb, Germany
  - Dr. Gerhard Woetting, Materials R&D
- U.S. Department of Energy
  - Debbie Haught, Washington
  - Steve Waslo, Chicago

28 Years Industry-Leading Experience In Ceramic Turbine Engine Technology Development

- **Integrated Approach is Key**
  - **Honeywell's strength and leadership position in ceramic technology results from vertically integrated capabilities**
- **Technology Development Focus Areas**
  - **Material advances**
  - **Ceramic design methodologies**
  - **Component mounting/retaining systems**
  - **Ceramic life prediction methodologies**
  - **Production Readiness Campaign**
- **First Generation Field Evaluations**
  - **85-series APU - radial-type ceramic nozzles 17,000+ hours**
    - **M32-60A ground carts - Luke AFB, AZ**
      1,875 hours/12,000 starts
  - **Eleven 85-98DHF APUs on Alaska Airlines MD-80s 40,000+ hours**
  - **331-250 APU nozzles on three A300-600 12,883 hours, 12,039 cycles**
  - **ASE8-800 industrial engine blisk 14,800+ hours**

The Power of Honeywell



Principal Commercialization Barriers

- Inadequate oxidation protection technology
- Inadequate facilities available to screen candidate substrate material and novel coating systems prior to high risk engine tests
- Immature low-cost near-net-shape fabrication processes
- Insufficient publicly available material design database of latest ceramic material vintage
- Unproven tip rub resistance
- Lower impact resistance than single crystal alloys
- Immature Cooled Component Fabrication

Honeywell's IR&D and Government-Funded Program Suite Addresses All Barriers And Enables Accelerated Commercialization of Ceramics in Small Gas Turbines

Motivation and Strategy

- Original Honeywell AMS contract did not adequately address critical ceramic component commercialization requirements
- New program strategy was required to develop the infrastructure and materials & process engineering disciplines necessary to overcome those barriers, which currently prevent structural ceramic component commercialization in advanced heat engines
- Revised program plan provides approach to resolve each of these issues and follows a natural progression based on past DOE-funded efforts at HES&S
- Focus will be on very near-term ceramic component production capability for premium gas turbine applications such as advanced industrial microturbines for distributed power generation
- Effort will draw heavily on "lessons learned" from the problems and successes on previously completed ceramics development and demonstration programs

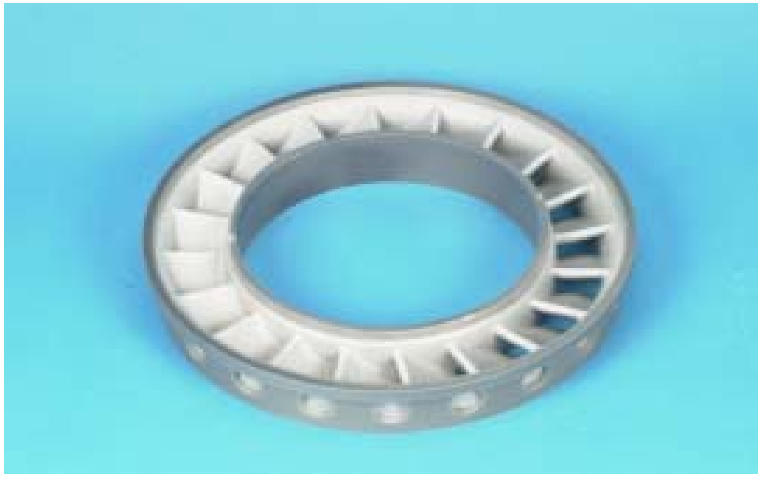
Work Breakdown Structure

Honeywell ES&S
Advanced Microturbines Systems
Related Activities

- **DOE AMS Program Award 2002 & 2003**
  - **Process Maturation**
  - **Database Generation**
  - **Oxidation Protection**
  - **Project Management**
- **Honeywell IR&D & Potential Government Programs**
  - **Design Processes**
    2002
    Honeywell IR&D
  - **Oxidation Protection**
    2002 & 2003
    Honeywell IR&D
  - **Engine Testing**
    2004 Optional
    DOE AMS Program Phase
  - **Field Evaluation**
    2004 & 2005 Optional
    DOE AMS Program Phase
- **Micoturbine OEM Support**
  (Selected OEM Through Separate Subcontracts)
  - **Ceramic Component Design Consultation**
  - **Life Prediction**
  - **Process Development**
    (Radial Turbine Components)
  - **Parts Fabrication**
  - **Database Generation**
    (Required)
  - **Spin Pit Testing**

Mature Low-Cost Near-Net-Shape Manufacturing Of Large Integral Ceramic Components

Nozzle Rings



Blisks

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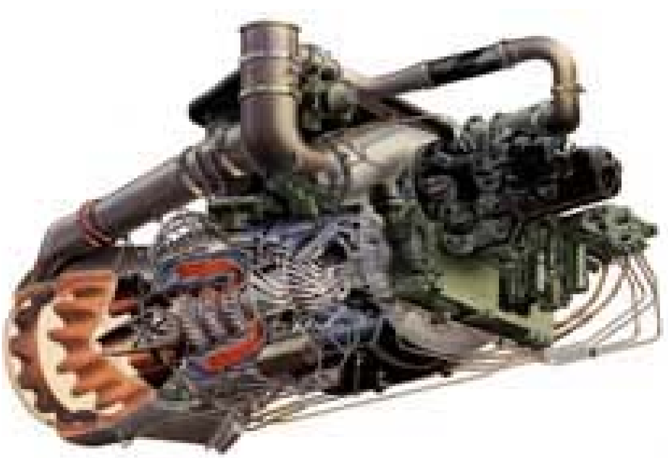
Radial Turbine Wheels

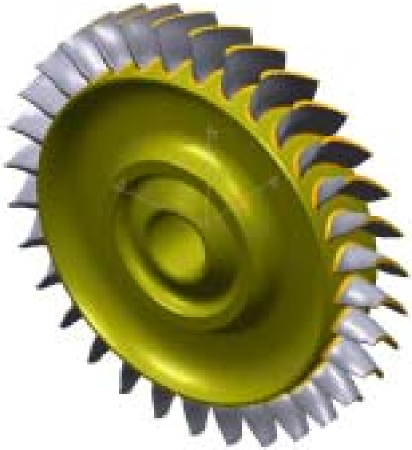
Top Level Summary

- Benefits to Selected Microturbine OEM
  - Delivery of high quality ceramic components
  - Mature low-cost near-net-shape fabrication process
  - Adequate oxidation protection
  - Joint development of publicly available material design database
  - Access to Honeywell ceramic gas turbine design & life prediction expertise
- Benefits to the Government
  - Protect past investment and build upon successes in ceramic gas turbine technology development
  - Participation of ORNL in key development activities
    - component characterization & database generation
    - oxidation protection system evaluation
  - UDRI (Mechanical Testing in Moist Environment)
  - Academia (Northwestern, Lehigh, UC Boulder) (EBC Fundamentals)
  - Argonne National Lab (NDE Characterization of EBCs)

Honeywell IR&D Programs

- Sintering Cycle Optimization
- Alternative Manufacturing Approaches
- Next Generation Silicon Nitride Material (ASN) Development
- Next Generation EBC Development
- Ceramic Hot Section Component Designs
- Design/Lifing Methodology Refinements
- Development Engine Testing
- Field Evaluation





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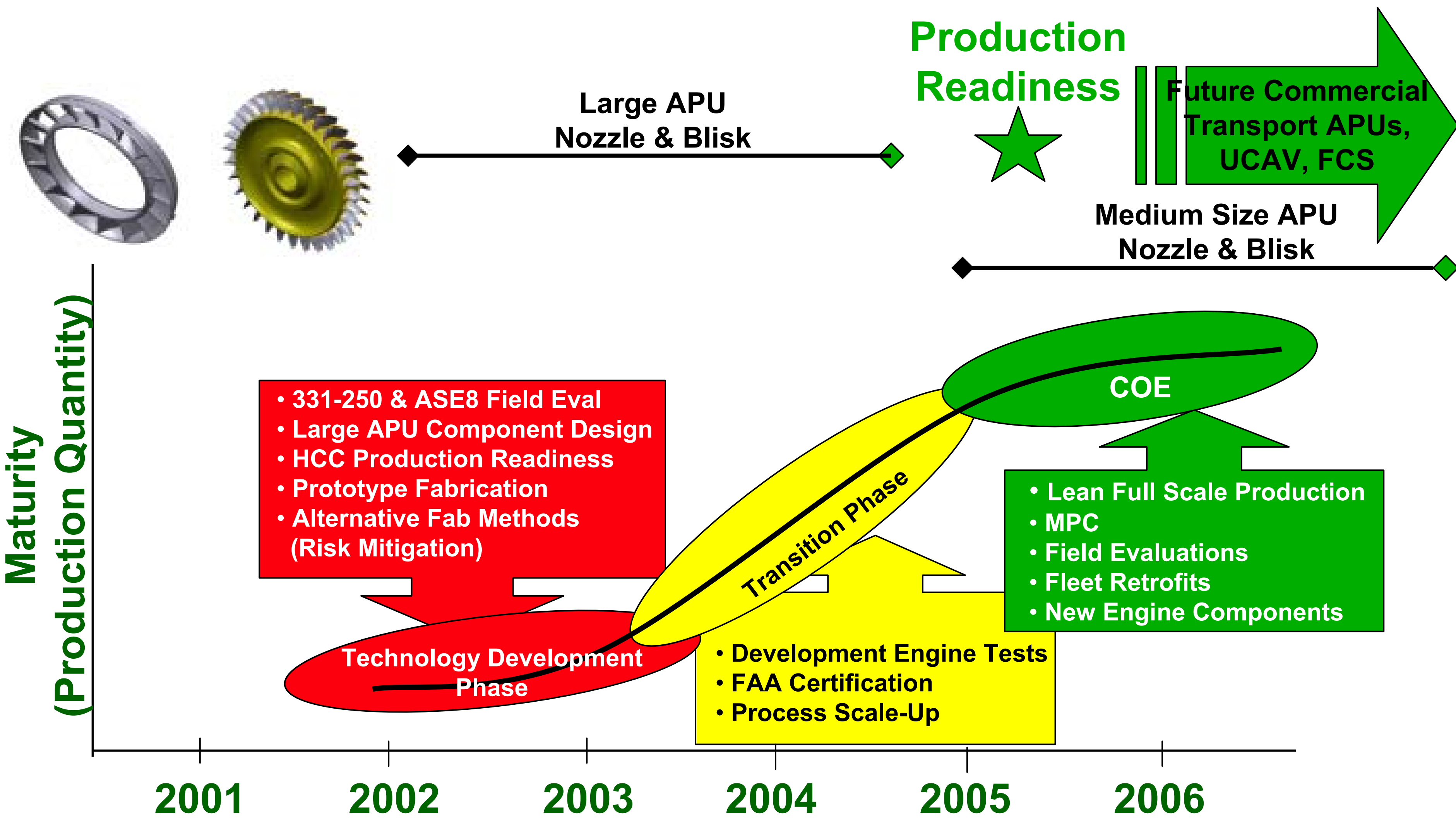
CAPU Ceramic Technology Insertion Plan



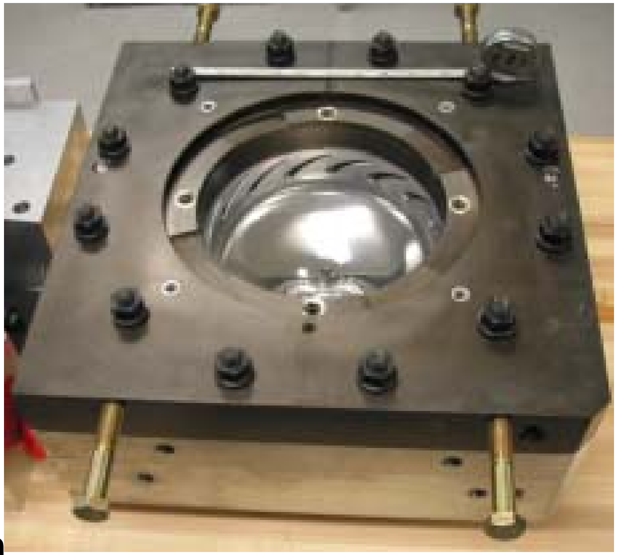
Technology Development Phase History

- Initiated development of net-shape gelcasting process for large APU integral nozzle ring and blisk 26 months ago
  - Gelcasting was perceived as the lowest cost process and needed to support larger volume projections
  - Focussed Six Sigma Plus efforts to understand and quantify process variation
    - Casting Defects
    - Material Properties
    - Dimensional Control
- *In Q1 2003 concluded gelcast process capability would not meet component requirements*
- Already in Q3 2002 initiated evaluation of alternative forming processes
  - Learned of success H.C. Starck (Germany) had with proprietary CIP and green machining as a low-cost forming process
  - Acquired exclusive process technology license
- Past 6 months focussed on CIP AS800 process evaluation and refinement

Nozzle Ring Development Tool

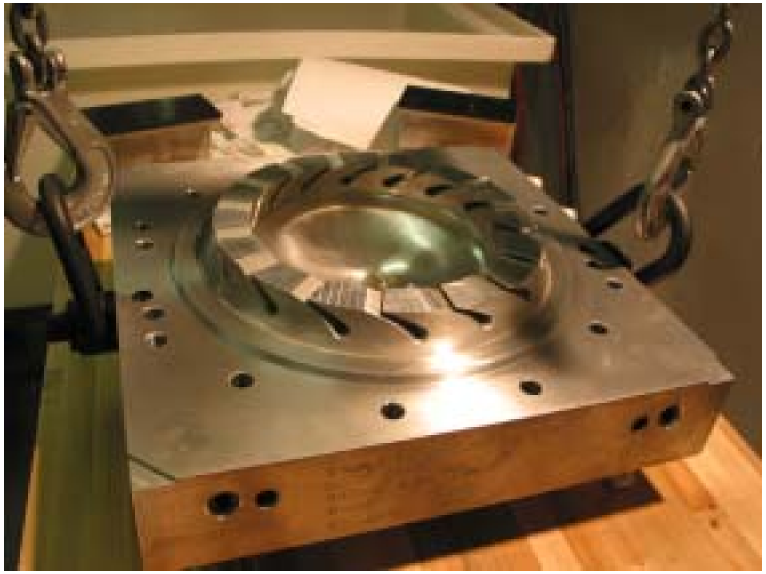
- The new tool design process was used to design and fabricate new nozzle ring development tool
- Realistic nozzle geometry
- Design similar to production tool
  - fill
  - venting
  - heating and cooling
  - assembly and disassembly
- Compatible with vacuum casting process

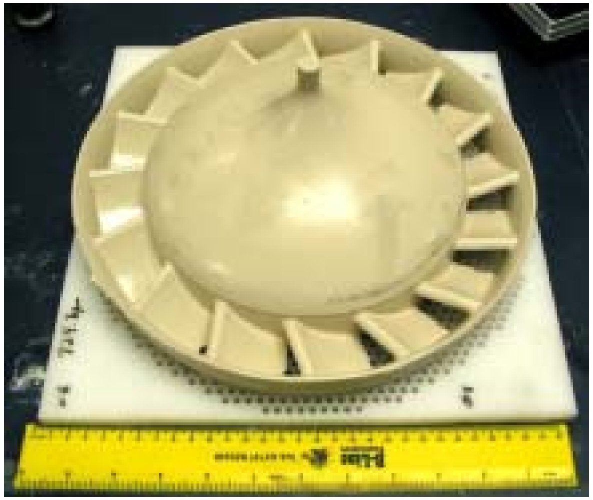




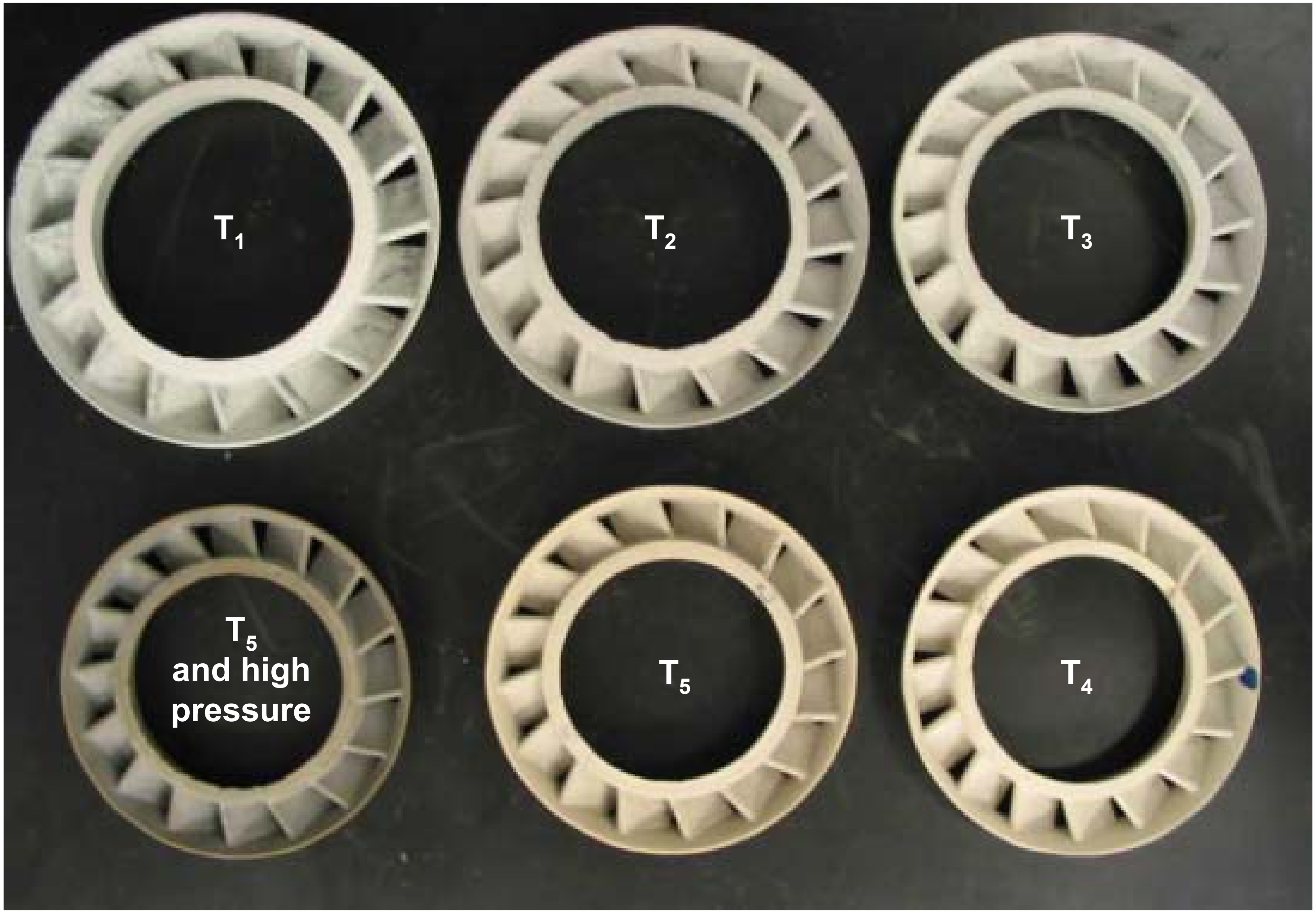

Nozzle Ring Development Tool

Nozzle Ring Development Tool (cont.)



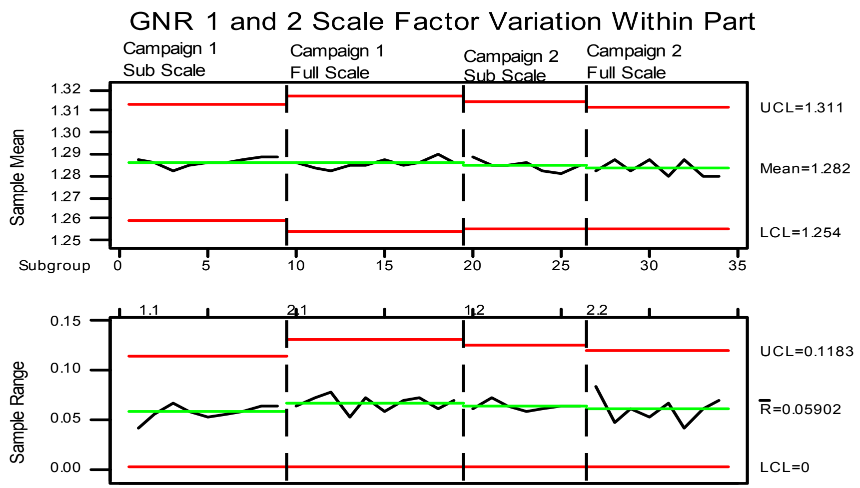


Interrupted Sintering Runs To Study Distortion

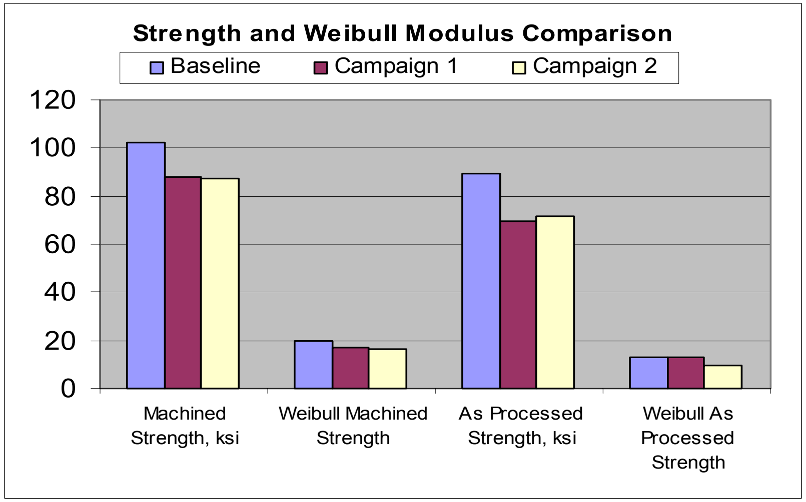


Gelcasting Findings & Conclusion

- Within part scale factor variation is 5.9% - too high to order tooling
- Large number of correlated factors control scale factor variation
- Significant scale factor variation & distortion occurs during final stages of sintering



- Machined and as processed surface mechanical properties of large component cut-ups are significantly lower than historical data on AS800
- Weibull modulus is also lower on both machined and as processed surface test specimens cut from components



Gelcasting Process May Not Be Capable Of Meeting Customer Requirements

Advanced Technology

Honeywell

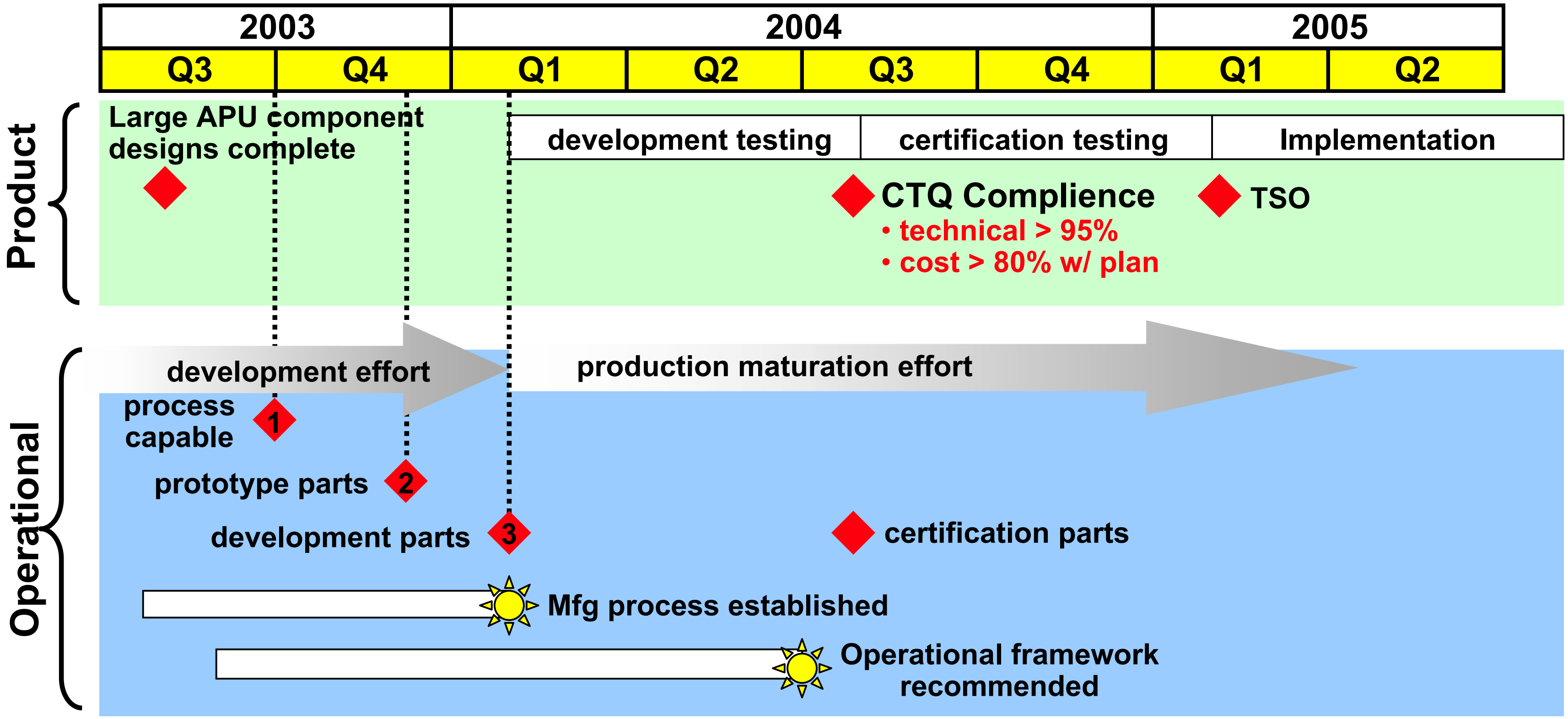
Remaining Gelcast Issues

- Defect and Variation Reduction
  - Defects caused by fill method
  - Defects caused by tool design
  - Variability of scale factor
    - Within part
    - Part to part
- Distortion
  - Thermal environment
  - Drag / sintering fixturing
  - Wet part handling / fixturing

Risk Mitigation

- Alternative Forming Approaches
  - Non-Aqueous Gelcasting
  - Slipcast & Bisque Machining
  - CIP & Green Machining
- Next Generation Substrate Material Development
  - Improved oxidation resistance
  - Stress rupture and creep properties similar to AS950EXP and SN282
  - Improved chemical interface compatibility with next generation EBC system

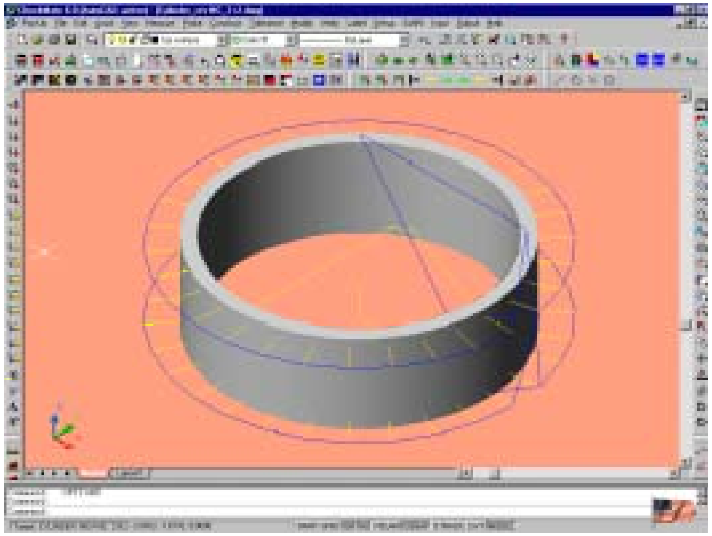
Operational Readiness Approach



Milestone 1: September 30, 2003
Fundamental Process Capability Assessment

- Available Forming Methods
  - Gelcast Net Shape (Baseline)
  - Slipcast & Presinter Machining (PSM)
  - Cold Isostatic Pressing (CIP) & PSM
  - CIP & Green Machining (GM)
- Sample Geometry
  - Large Thin-Walled Ring (6.25” OD, 1.4” height, 0.20” wall thickness)
- Go/No-Go Criteria
  - Roundness of 50% of the parts manufactured by the most capable process has to be equal or better than 0.020”
  - Positional Error (True Position) with respect to OD mid position (datum) of 50% of the parts manufactured by the most capable process has to be equal or better than 0.004”

Process Capability Assessment Roundness & True Position



- 30 individual data points taken at OD at 3 different heights, respectively
- Center of “best fit” circle through mid-plane OD data points represents datum
- **Roundness** is defined as the radial distance between two concentric circles forming the tightest band that includes all 30 points
- **Positional Error** (True Position) is defined as twice the radial displacement of the axis of the considered feature to the datum
- **Cylindricity** (not required) is defined as the radial distance between two concentric cylinders forming the tightest band that includes all 90 points

Process Capability Assessment Results

Forming Process	Roundness *	Positional Error *	Cylindricity **
Gelcast Net Shape	0.056"	0.011"	N/A (draft angle)
Slipcast & Presinter Machining	0.037"	0.005"	0.051"
Cold Isostatic Pressing (CIP) & PSM	0.012"	0.002"	0.0178"
CIP & Green Machining (GM)	0.0186" (0.0067")***	0.002"	0.023" (0.0154")***
Target	0.020"	0.004"	0.020" **

* Maximum of the 3 different measurement plane values (top, middle, bottom)

** Not required to pass go/no-go gate (good indication for achievable surface profile tolerance though)

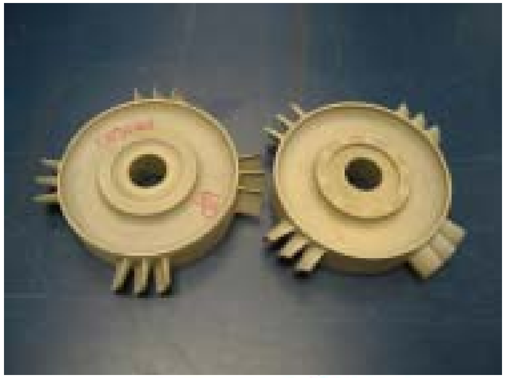
*** Achieved at IKTS using modified sintering cycle in smaller furnace for 5.5" OD rings

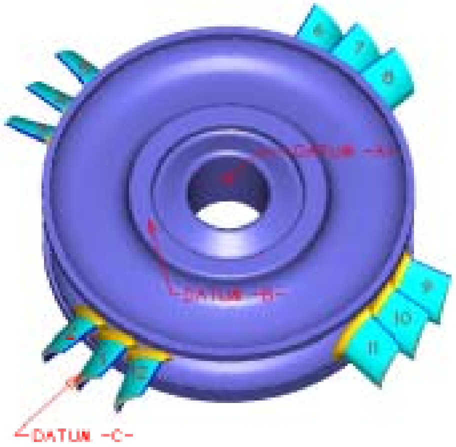
Conclusions

- Successfully passed first go/no-go gate (Milestone 1)
  - Process capability regarding distortion: CIP > Slipcast >> Gelcast
- Green machining would allow meeting cost target, while PSM would present significant manufacturing cost challenge
  - Go-forward with CIP & PSM for Milestone 2 & 3
  - Develop and transition CIP & GM from H.C. Starck in parallel to address fab cost

Milestone 2: November 30, 2003
Prototype Fabrication Capability

- **Sample Geometry**
  - 8” OD paddle wheel to assess airfoil distortion
- **Batch Size**
  - 4 paddle wheels using best process
- **Go/No-Go Criteria**
  - Roundness of rim OD has to be equal or better than 0.015” for 50% of the parts
  - Surface profile tolerance of 0.020” (+/-0.010”) with respect to center line datum structure met for all blades of 50% of the parts
  - Actual position of all blades on the rim has to be within 0.010” (+/-0.005”) of nominal position as defined by print





Milestone 2
Interim Results

- Rim roundness less than 0.008” for 100% of parts
- Disk droop less then 0.005”
- Airfoil profile tolerance less than 0.015”
  - includes consistent twist ($<1^{o}$) of airfoils (sintering distortion)
  - will be corrected in next iteration by changing CMM program
- Process optimization of spray drying, CIP, and sintering cycle underway
- GM allows one order of magnitude reduction of machining cost

CIP and PSM or GM process seems capable of meeting dimensional and cost requirements of large complex components

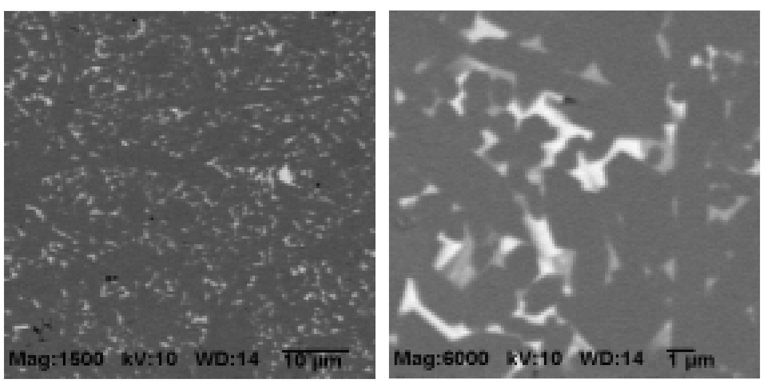
Milestone 3: January 31, 2004 Development Engine Test Hardware

- Sample Geometry
  - Nozzle Ring per production print
  - Blisk per production print
- Batch Size
  - 4 parts per component using final process in order to yield at least 2 parts per component meeting criteria below for delivery
- Go/No-Go Criteria
  - 50% of the parts manufactured by the final process have to be within +/- 5% of the dimensional tolerance requirements of production print
  - The following mechanical properties of co-processed material have to be within 95% of current EMS53192
    - room temperature flexural strength
    - dynamic fatigue at 2200F for 0.003 and 30 MPa/s
  - Present credible plan to demonstrate 80% of fab cost goal by June 2004

Ceramic Materials Development
Advanced Silicon Nitride (ASN)

- Ongoing Honeywell IR&D Program
- ASN material development for extended use at 1,400C (2,550F) material temperature
- Robust gas pressure sintering process, in-situ reinforced (ISR) microstructure
- Maintain superior design characteristics of benchmark Honeywell AS800 Si_3N_4
  - K_{Ic} > 7 MPa $m^{0.5}$, m > 20, RT FF strength > 90 ksi, 1,400C FF strength > 70 ksi
- Similar long term HT properties relative to benchmark Kyocera SN282 Si_3N_4
  - Oxidation Resistance: weight gain after 1,000 hours at 1,400C < 1.0 mg cm^{-2}
  - Creep Resistance: steady state creep rate (4P-bend) at 1,400C and 200 MPa < 1.0×10^{-9} s^{-1}
- Chemically compatible with Honeywell's next generation OBC/EBC system

ASN ISR Microstructure



Results Achieved To Date

- Chemical constituents and compositional window established
- RT FF strength: 100 ksi
- 1,400C FF strength: 80 ksi
- Weibull modulus m: 32
- K_{Ic}: 8 MPa $m^{0.5}$
- Weight gain (1,000 hours, 1,400C): 0.7 mg cm^{-2}
- Creep rate (1400C): TBD (testing initiated)

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Summary & Conclusions

- Enabling technology and infrastructure development in progress
- Various forming methods for large integral components evaluated
- CIP and GM clearly the only capable low-cost process
- Efforts in 2004 need to focus on
  - making prototype engine parts
  - process scale-up and maturation (fixed process)
  - demonstration of cost target
- Next generation material (ASN) for higher temperature microturbines already in the development & transition pipeline